AD-775 626

MAN'S PERFORMANCE DEGRADATION DURING SIMULATED SMALL BOAT SLAMMING

Herbert Wolk, et al

Naval Ship Research and Development Center
Bethesda, Maryland

January 1974

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UNCLASSIFIED
Security Classification

AD 775 626

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Naval Ship Research and Development Center
Bethesda, Maryland 20034

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
MAN'S PERFORMANCE DEGRADATION DURING SIMULATED SMALL BOAT SLAMMING

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)
Herbert Wolk and John F. Tauber, M.D.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1974	52	63

8a. CONTRACT OR GRANT NO.
IR-NSRDC Elements 61101N & 61151N
b. PROJECT NO. R01101 & ZR60001
Task ZR0110101 & 0230301
Work Unit 1747-373
d.

9a. ORIGINATOR'S REPORT NUMBER(S)
4234

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
Approved for public release: distribution unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Naval Ship Research & Development Center
Bethesda, Maryland 20034

13. ABSTRACT

A research program has been developed and preliminary data obtained on man's performance in a repetitive slamming environment such as would be encountered in a high-performance craft traversing rough seas.

The Naval Ship Research and Development Center (NSRDC) slam simulator was used to test human volunteers in two series of laboratory-controlled studies that simulated ship slamming. The results indicate (1) that man's performance is degraded in a slamming environment (2) that the subjective reactions of the volunteers do not reflect their performance scores (3) that the test data are highly reproducible, and (4) that only minor muscular skeletal discomforts occurred during the test sessions. The report includes background material on man's known tolerance to single impacts and vibration.

DD FORM 1 NOV 65 1473 (PAGE 1)
S/N 0101-807-6801

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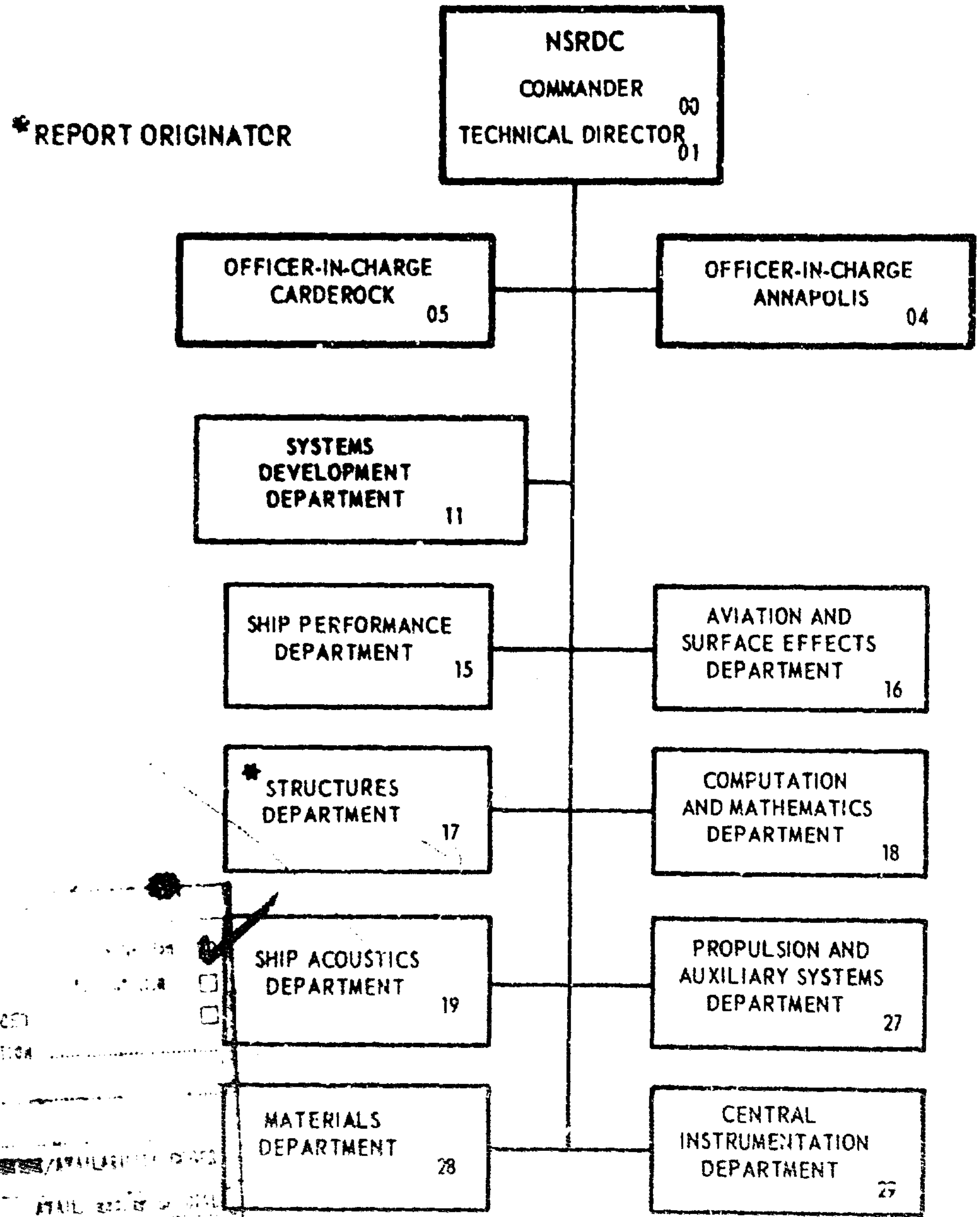
MAJOR NSRDC ORGANIZATIONAL COMPONENTS



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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Small Boat Slamming						
Simulated Slamming						
Man's Performance Degradation						
Human Tolerance to Slamming						
Sea State						

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by

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J.F. Tauber, M.D.

January 1974 Report 4234

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ABSTRACT

A research program has been developed and preliminary data obtained on man's performance in a repetitive slamming environment such as would be encountered in a high-performance craft traversing rough seas.

The Naval Ship Research and Development Center (NSRDC) slam simulator was used to test human volunteers in two series of laboratory-controlled studies that simulated ship slamming. The results indicate (1) that man's performance is degraded in a slamming environment (2) that the subjective reactions of the volunteers do not reflect their performance scores (3) that the test data are highly reproducible, and (4) that only minor muscular skeletal discomforts occurred during the test sessions. The report includes background material on man's known tolerance to single impacts and vibration.

ADMINISTRATIVE INFORMATION

This research program was conducted under the in-house independent research program of NSRDC. Funding was provided under Program Elements 61101N and 61151N, Projects R01101 and ZR00001, Task Areas ZR0110101 and 0230301, Work Unit 1747-373. A large portion of this text has been extracted from four informal progress reports.* Many of the authors of those reports have since left NSRDC but their contributions to the program cannot be ignored.

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*Progress was reported as enclosures to NSRDC letters:

Enclosure 1 (A Research Program to Investigate Man's Performance Capabilities in a Repetitive Impact Environment, by Strother, C.F. and Corrao, P., MD) to NSRDC letter Serial 69-740-1399 of 2 December 1969.

Enclosure 1 (Man's Performance Capability in a Repetitive Impact Environment Imposed on 50- to 100-foot Craft in Sea Conditions up to State 4: Documented Background Studies and Planned Experimental Method Submitted in Support of Requests to Use Human Volunteers as Subjects, by Tauber, J.F., Willner, A.R., Gesswein, J., and Corrao, P., MD) to NSRDC letter Serial 70-740-1529 of 27 June 1970.

Enclosure 1 (Progress Report on Man's Tolerance to Repetitive Impacts, by Mahone, R.M., Diachok, D., and Corrao, P., MD) to NSRDC letter Serial 71-740-1551 of June 1971.

Enclosure 1 (Progress Report on Degradation of Man's Performance under Simulated Slamming Conditions, by Wolk, H. and Diachok, D.) to NSRDC letter Serial 72-174-532 of 7 December 1972.

OBJECTIVE

A research program has been developed and preliminary data obtained on man's performance in a repetitive slamming environment such as would be encountered in a high-performance craft traversing rough seas. The overall objective is to improve the endurance and performance of Navy crews through the development of design concepts that reduce to tolerable limits the slamming motions to which they are subjected during small boat operations in rough seas. The program called for using the NSRDC slam simulator to obtain laboratory determination of the levels of repetitive slamming motions which affect crew endurance and performance. This report presents preliminary data obtained on the slam simulator. The purpose was (1) to evaluate the difference in tracking performance of human volunteers with and without being subjected to a variety of impact conditions and (2) to determine the reproducibility of the test data, e.g., whether a single score truly indicates the ability to track at a particular test session.

INTRODUCTION

BACKGROUND

For many years, the problem of ship bottom slamming has been recognized as a source of damage to ships,[1-5] but past investigations were concerned with improving the structural features and seaworthiness of ships rather than with the effects on slamming on ship crews.

It has been suggested that the rough sea corresponds to the sonic barrier in aerodynamics and that the maximum speed of a surface vessel is determined not by its power but by its behavior in a seaway. Present interest in faster and lighter ships has focused emphasis on a new and very important aspect of the investigations of ship slamming, that of man's performance and tolerance. To date, little account has been taken of the well-being or endurance of the

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[1] Szebehely, V.G. and M.A. Todd, "Ship Slamming in Head Seas," David Taylor Model Basin Report 913 (Feb 1955). (A complete list of references appears on pages 44–48.)

[2] Szebehely, V.G. and M.A. Todd, "Model Experiments on Slamming of a Liberty Ship in Head Seas," David Taylor Model Basin Report 914 (Feb 1955).

[3] Jasper, N.H., "Dynamic Loading of a Motor Torpedo Boat (YP-110) during High-Speed Operation in Rough Water," David Taylor Model Basin Report C-175 (Sep 1949).

[4] Henry, J.R. and F.C. Bailey, "Slamming of Ships: A Critical Review of Current State of Knowledge," Ship Structure Committee, U.S. Coast Guard Report SSC-208 (1970).

[5] Wheaton, J.W. et al., "Analysis of Slamming Data from the S.S. WOLVERINE STATE," Ship Structure Committee, U.S. Coast Guard Report SSC-210 (1970).

crew and no investigative work has been done on their tolerance to repetitive impact. (See Appendix A for detailed information on biomechanical studies.) Man's tolerance to single impacts (Figure 1) has been established,[6] and man's response to a vibrational environment has been studied very carefully.[7-19] These two sources of data, single impact and vibration studies, provided rough criteria from which to begin establishing tolerance, endurance, and performance criteria for repetitive impacts.

DEFINITIONS AND CONDITIONS OF SLAMMING

The phenomenon of slamming results when a ship bow emerges from the water and subsequently submerges with a certain magnitude of relative velocity between wave and ship.

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[6]Mahone, R.M., "Man's Response to Ship Shock Motions," David Taylor Model Basin Report 2135 (Jan 1966).

[7]Bender, F.K. and A.M. Collins, "Effects of Vibration on Human Performance: A Literature Review," Final Report for NSRDC by Bolt Beranek and Newman, Inc., under Contract N00014-69-C-0095, BBN Report 1767 (15 Feb 1969).

[8]Townsend, J.C., "Effects of Vertical Vibration on the Well Being of Surface Effect Ship (SES) Personnel: Literature Survey," Final Report 209/67 under Contract No. N00161-67-C-0172 with Marine Engineering Laboratory U.S. Navy (Mar 1967).

[9]Lee, R.A. and F. Pradko, "Theory of Human Vibration Response," ASME Paper 66-WA/BHF-15 (Nov 1966).

[10]Edwards, R.G. and K.O. Lange, "A Mechanical Impedance Investigation of Human Response to Vibration," Wenner-Gren Aeronautical Research Laboratory (Oct 1964).

[11]Von Gierke, H.E. and R.R. Coermann, "The Biodynamics of Human Response to Vibration and Impact," Industrial Medicine and Surgery, pp. 30-32 (Jan 1963).

[12]Magid, E.B. et al., "Physiological and Mechanical Response of the Human to Longitudinal Whole Body Vibration as Determined by Subjective Response," Biomedical Laboratory WPAFB, Tech. Document Report MRL-TDR-62-66 (Jun 1962).

[13]Magid, E.B. et al., "Human Tolerance to Whole Body Sinusoidal Vibration," Aerospace Medicine, pp. 915-924 (Nov 1960).

[14]Van Deusen, B.D., "Human Response to Vehicle Vibration," SAE Report 680090 (Jan 1968).

[15]Buchmann, E., "Criteria for Human Reaction to Environmental Vibration on Naval Ships," David Taylor Model Basin Report 1635 (Jun 1962).

[16]Clarke, N.P. et al., "Evaluation of Peak versus RMS Accelerations in Periodic Low Frequency Vibration Exposures," Aerospace Medicine, Vol. 36, No. 11, pp. 1083-1089 (Nov 1965).

[17]Pradko, F. et al., "Human Vibration-Response Theory," ASME Report 65-WA/HUF-19 (Aug 1965).

[18]Terry, C.T. and V.L. Roberts, "A Viscoelastic Model of the Human Spine Subjected to +gz Accelerations," Journal of Biomechanics, Vol. 1, No. 2, pp. 161-168 (Jul 1968).

[19]MacDuff, J.N., "Transient Testing of Man," Journal of Sound and Vibration, pp. 16-21 (Aug 1969).

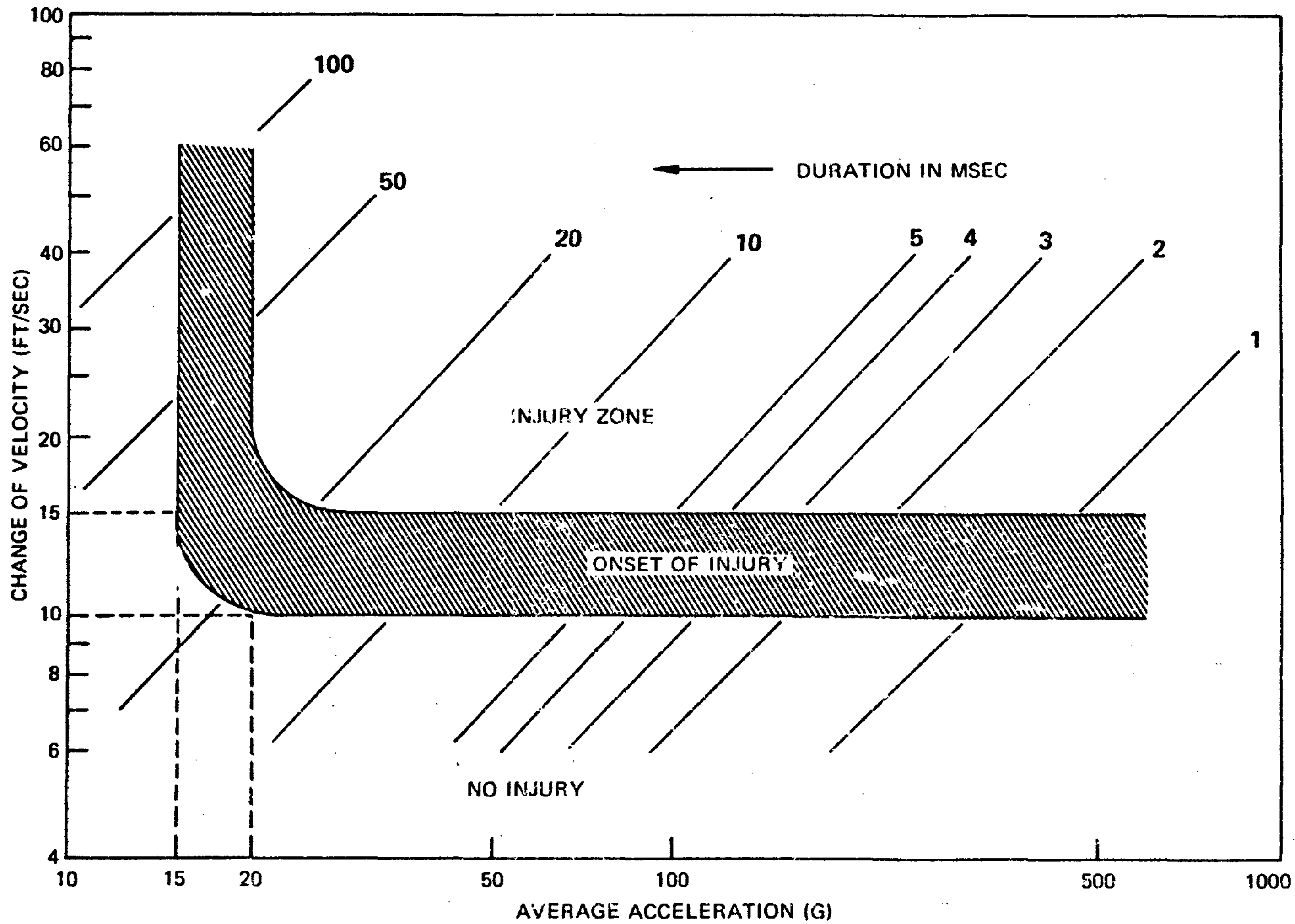

Figure 1 – Man's Tolerance to Single Impacts

The relative velocity required to induce slamming has been defined by Ochi[20] as the "threshold velocity" and is the minimum velocity which will cause slamming. Any relative velocity below threshold velocity will not cause slamming. Ochi has evaluated experimental data from various sources and has found that the threshold velocity for a 520-ft ship is nearly constant with an average of 12 ft/sec. He points out that the threshold velocity V can be modified for ships of other lengths by using Froude scaling:

$$F = V/\sqrt{gL} = \text{constant} \tag{1}$$

Therefore to calculate the threshold velocity V for a ship of any length L, all one has to do is substitute the appropriate values into Equation (1). For a ship length L = 50 ft, e.g.:

$$F = V/\sqrt{gL} = 12/\sqrt{520 \times g} = v/\sqrt{50 \times g}$$

$$v = \frac{12\sqrt{50 \times g}}{\sqrt{520 \times g}}$$

$$v = 3.7 \text{ ft/sec or } 2.2 \text{ knots}$$

The scaling law, Equation (1), was used to derive Figure 2 which gives the threshold velocity V as a function of ship length L.

The three major parameters used to describe slamming conditions are (1) the peak deck acceleration (usually given in g's), (2) the frequency of impact (usually given in slams per minute), and (3) the duration of the acceleration pulse (usually given in milliseconds).

The acceleration-time history that the deck imposes on man will be a function of the magnitude of the threshold velocity, the wave form, and the ship hull form, heading, and speed. Figure 3 shows typical acceleration time histories of slams.[21] Slam accelerations can reach as high as 10 g, with durations from 20 to 200 msec depending on the aforementioned factors.[22]

The frequency with which the slamming phenomenon occurs is also a very important factor that has to be related to man's performance and endurance. To date, the best

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[20]Ochi, M.K., "Prediction of Occurrence and Severity of Ship Slamming at Sea," Fifth Symposium on Naval Hydrodynamics, ONR U.S.A. and Snipmodeltanken, Bergen, Norway (Sep 1964).

[21]Mahone, R.M. and H.L. Wolk, "Final Report on the Development of a Slam-Mitigating System for Crew Use: Evaluation during Sea Trials aboard an OSPREY-Class PTF," NSRDC Report 4008 (Jan 1973).

[22]Chuang, S., "Slamming Tests of Structural Models Representing a Ship Bottom with 10-Degree Deadrise Angle - General Outline of Tests and Test Results," NSRDC Report 3007 (Aug 1969).

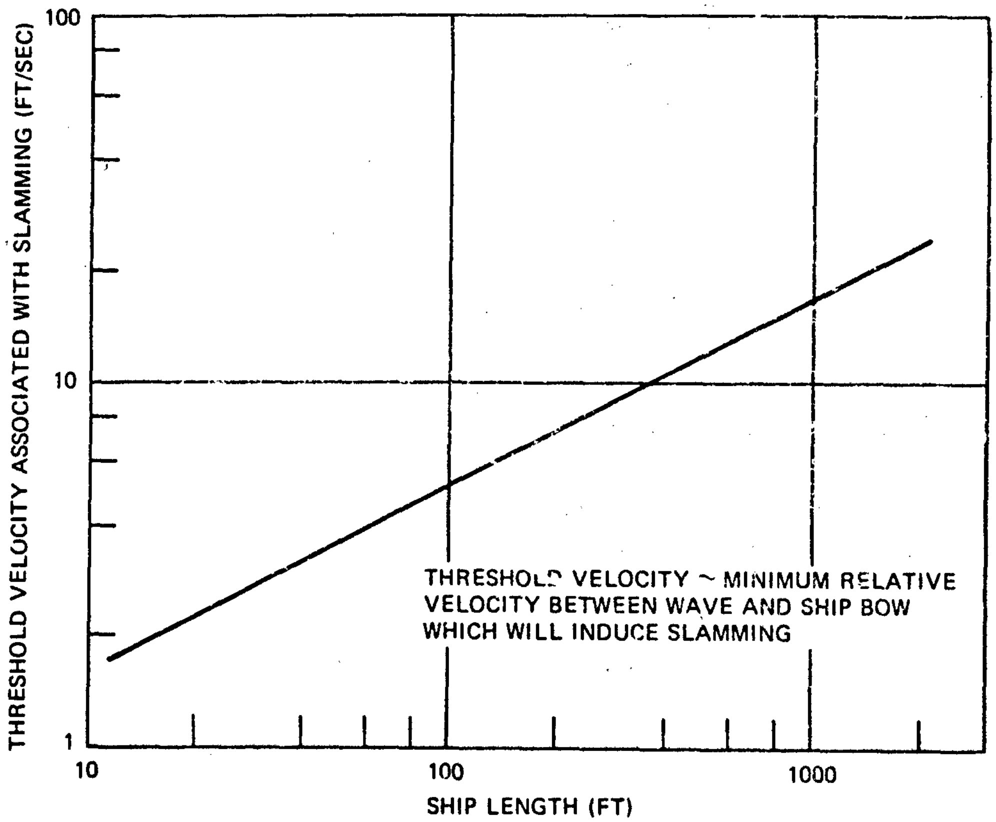

Figure 2 – Threshold Velocity Associated with Slamming as a Function of Ship Length

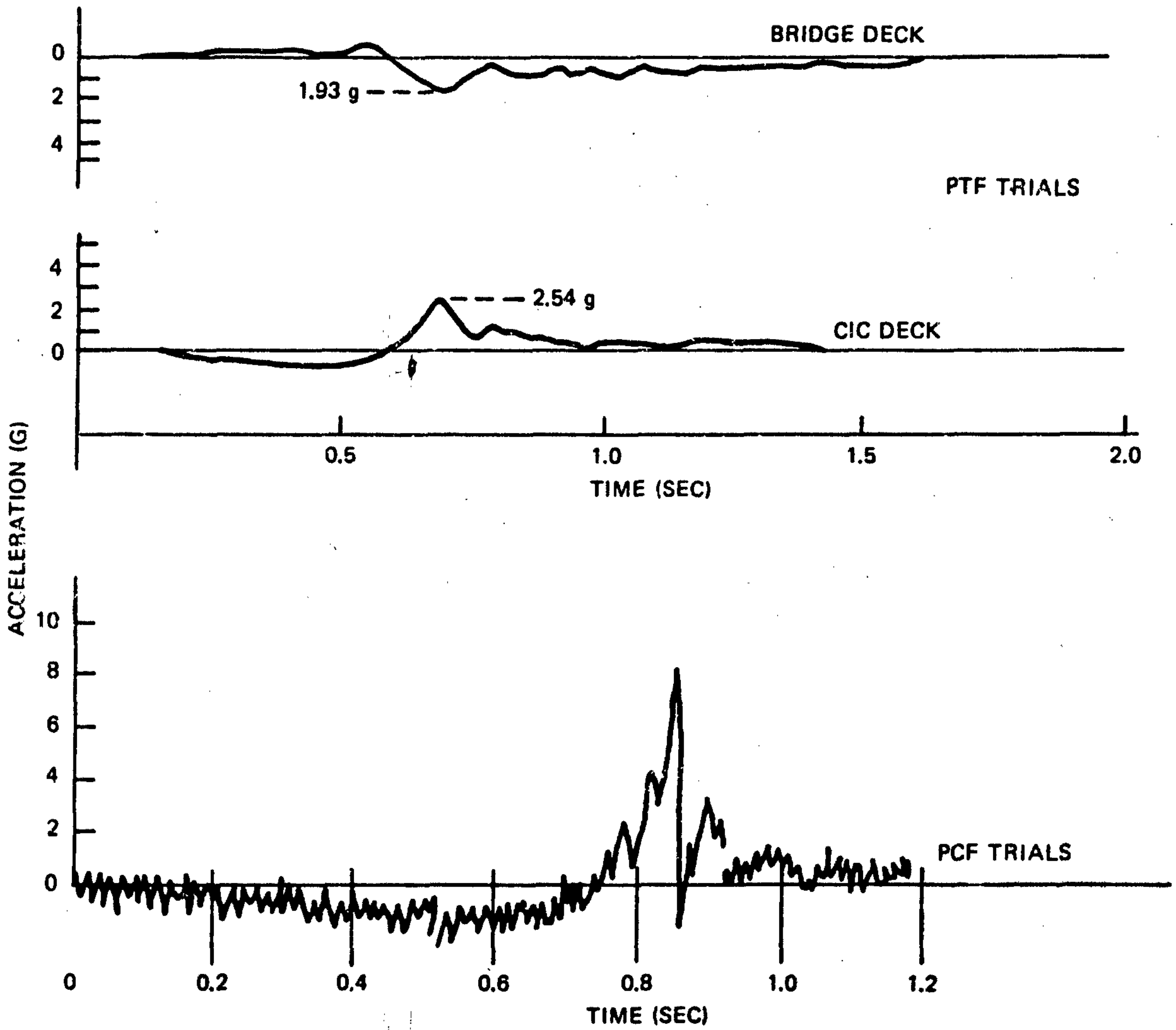

Figure 3 – Acceleration-Time History of a Typical Slam

available physical description of the sea defines conditions in terms of a number of sea states; these can be found in any encyclopedia of nautical knowledge. The distinction between various sea states is indicated in Table 1. The sea state and the length, speed, and direction of the ship with respect to the waves all affect the frequency with which a boat will slam.

The following equation can be used to calculate the frequency of encounter, i.e., the frequency with which the boat encounters a wave:

$$W_e = W_w + \frac{V_B}{L_w} \tag{2}$$

where W_e is the frequency of encounter in crests per second,

W_w is the frequency of the wave in crests per second,

V_B is the boat speed in feet per second, and

L_w is the wave length in feet.

Sample Calculation:

If a State 4 sea is assumed, then the following is known from Table 1:

$$W_w = 0.200 \text{ crest/sec and } L_w = 90 \text{ ft}$$

Now assume a boat speed V_B = 35 knots. Substituting into Equation (2) and solving for the frequency of encounter W_e:

$$\begin{aligned} W_e &= W_w + \frac{V_B}{L_w} \\ &= 0.200 + 35 \text{ knots} \times \frac{1 \text{ ft/sec}}{0.5925 \text{ knots}} \times \frac{1}{90 \text{ ft}} \\ &= 0.857 \text{ crest/sec} \end{aligned}$$

Therefore, the frequency of encounter will be 0.857 crest/sec (51 slams/min) and the maximum slamming frequency cannot be larger than the frequency of encounter. For the worse possible case, the slam frequency W_s will equal the frequency of encounter W_e.

Figure 4 was derived by repeating the above calculations to obtain the maximum frequency of slams as a function of craft speed for the maximum and minimum wave lengths as prescribed by a State 4 sea. In order to document the relationships of sea state, boat speed, slam frequency, and peak accelerations, somewhat more precisely, NSRDC personnel instrumented a PCF and PTF and made measurements during test runs. The following results were obtained:

TABLE 1 – GENERAL PHYSICAL DESCRIPTION OF SEA STATES

Sea State[1]	Description[2]	(Beaufort) Wind Force	Description	Range (knots)	Wind Velocity (knots)	Wave Height Feet: Average	Wave Height Feet: Significant	Wave Height Feet: Average 1/10 Highest	Significant Range of Periods (seconds)	T_{max} (Period of Max Energy of Spectrum)	$\bar{T}$ (Average Period)	$\bar{L}$ (Average Wave Length)	Minimum Fetch (Nautical Miles)	Minimum Duration (Hours)
	Wind and Sea Scale for Fully Arisen Sea													
	Sea General		Wind[1]			Sea[3]								
0	Sea like a mirror	0	Calm	Less than 1	[a] 0	0	0	0						
	Ripples with the appearance of scales are formed but without foam crests	1	Light Airs	1 3	2	0.05	0.08	0.10	Up to 1.2 sec	0.7	0.5	10 in	5	18 min
	Small wavelets, still short but more pronounced crests have a glassy appearance, but do not break	2	Light Breeze	4 6	5	0.18	0.29	0.37	0.4 2.8	2.0	1.4	6.7 ft	8	39 min
1	Large wavelets, crests begin to break. Foam of glassy appearance. Perhaps scattered white horses	3	Gentle Breeze	7 10	8.5	0.6	1.0	1.2	0.8– 5.0	3.4	2.4	20	9.8	1.7 hrs
					10	0.88	1.4	1.8	1.0 6.0	4	2.9	27	10	2.4
2	Small waves, becoming larger, fairly frequent white horses.	4	Moderate Breeze	11 16	12	1.4	2.2	2.8	1.0 7.0	4.8	3.4	40	18	3.8
					13.5	1.8	2.9	3.7	1.4 7.6	5.4	3.9	52	24	4.8
					14	2.0	3.3	4.2	1.5 7.8	5.6	4.0	59	28	5.2
3					16	2.9	4.6	5.8	2.0– 8.8	6.5	4.6	71	40	6.6
4	Moderate waves, taking a more pronounced long form, many white horses are formed. (Chance of some spray)	5	Fresh Breeze	17 21	18	3.8	6.1	7.8	2.5 10.0	7.2	5.1	90	55	8.8
					19	4.3	6.9	8.7	2.8 10.6	7.7	5.4	99	65	9.2
					20	5.0	8.0	10	3.0 11.1	8.1	5.7	111	75	10
5	Large waves begin to form, the white foam crests are more extensive everywhere. (Probably some spray).	6	Strong Breeze	22 27	22	6.4	10	13	3.4 12.2	8.9	6.3	134	100	12
					24	7.9	12	16	3.7 13.5	9.7	6.8	160	130	14
					24.5	8.2	13	17	3.8 13.6	9.9	7.0	164	140	15
6					26	9.6	15	20	4.0 14.5	10.5	7.4	188	180	17
	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. (Spindrift begins to be seen).	7	Moderate Gale	28 33	28	11	18	23	4.5 15.5	11.3	7.9	212	230	20
					30	14	22	28	4.7 16.7	12.1	8.6	250	280	23
					30.5	14	23	29	4.8 17.0	12.4	8.7	258	290	24
					32	16	26	33	5.0 17.5	12.9	9.1	285	340	27
7	Moderately high waves of greater length, edges of crests break into spindrift. The foam is blown in well marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh Gale	34 40	34	19	30	38	5.5 18.5	13.6	9.7	322	420	30
					36	21	35	44	5.8 19.7	14.5	10.3	363	500	34
					37	23	37	46.7	6–20.5	14.9	10.5	376	530	37
					38	25	40	50	6.2 20.8	15.4	10.7	392	600	38
					40	28	45	58	6.5 21.7	16.1	11.4	444	710	42
8	High waves. Dense streaks of foam along the direction of the wind. Sea begins to roll. Visibility affected.	9	Strong Gale	41 47	42	31	50	64	7 23	17.0	12.0	492	830	47
					44	36	58	73	7–24.2	17.7	12.5	534	960	52
					46	40	64	81	7 25	18.6	13.1	590	1110	57
	Very high waves with long overhanging crests. The resulting foam is in great patches and is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes a white appearance. The rolling of the sea becomes heavy and shocklike. Visibility is affected	10	Whole Gale*	48 55	48	44	71	90	7.5 26	19.4	13.8	650	1250	63
					50	49	78	99	7.5 27	20.2	14.3	700	1420	69
					51.5	52	83	106	8–28.2	20.8	14.7	736	1560	73
					52	54	87	110	8–28.5	21.0	14.8	750	1610	75
					54	59	95	121	8 29.5	21.8	15.4	810	1800	81
9	Exceptionally high waves (small and medium-sized ships might for a long time be lost to view behind the waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	11	Storm*	56 63	56	64	103	130	8.5 31	22.6	16.3	910	2100	88
					59.5	73	116	148	10 32	24	17.0	985	2500	101
	Air filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	12	Hurricane*	64–71	> 64	> 80[b]	> 128[b]	> 164[b]	10–(35)	(20)	(10)	–	–	–

This table compiled by Wilbur Marks, David Taylor Model Basin.

*For hurricane winds (and often whole gale and storm winds) required durations and fetches are rarely attained. Seas are therefore not fully arisen.

a) A heavy box around this value means that the values tabulated are at the center of the Beaufort range.

b) For such high winds, the seas are confused. The wave crests blow off, and the water and the air mix.

1) Encyclopedia of Nautical Knowledge, W.A. McEvan and A.H. Lewis, Cornell Maritime Press, Cambridge, Maryland, 1953, p. 488.

2) Manual of Seamanship, Volume II, Admiralty, London, H.M. Stationary Office, 1952, pp. 717–718.

3) Practical Methods for Observing and Forecasting Ocean Waves, Pierson, Neuman, James, N.Y. Univ. College of Engin, 1953.

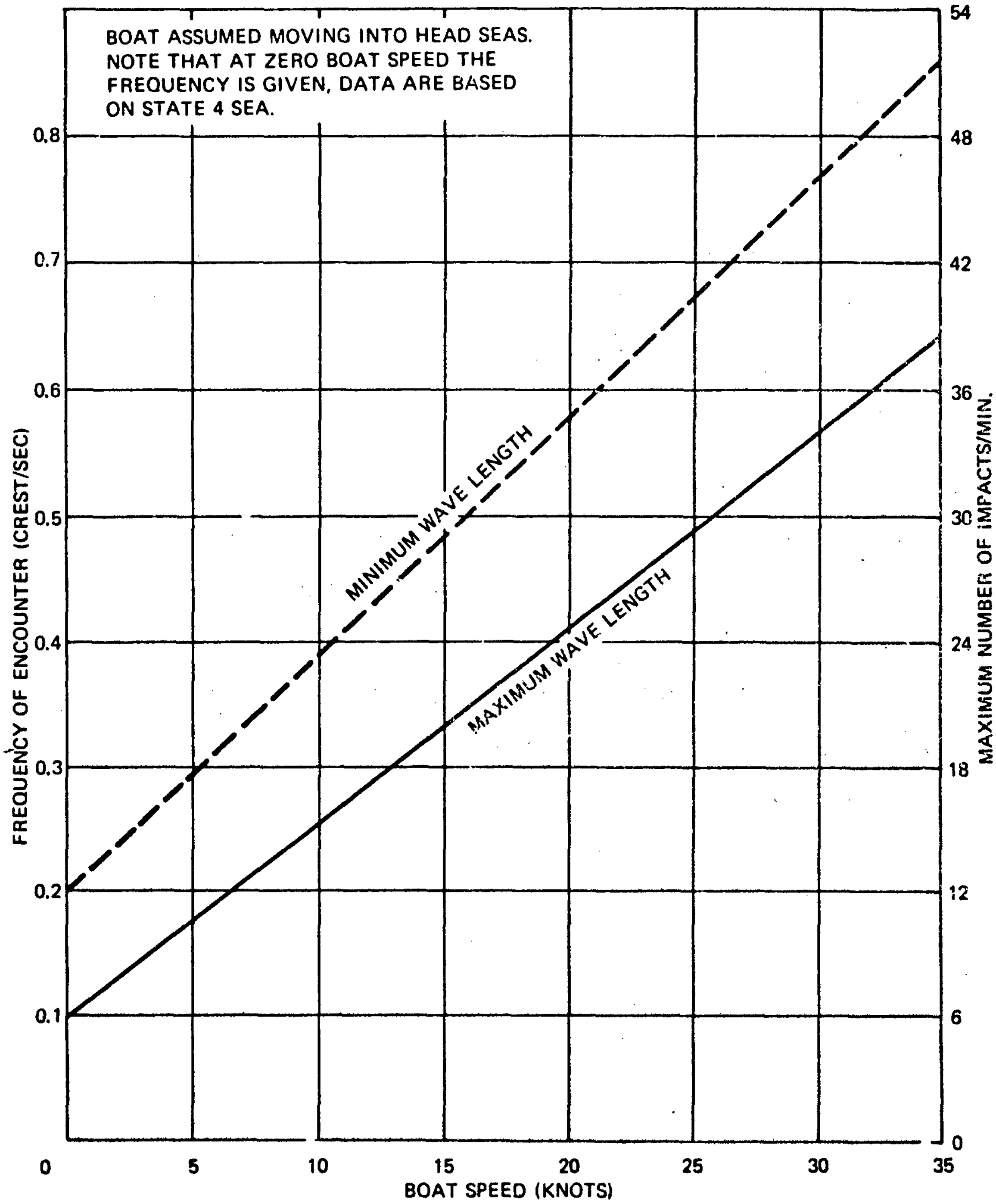

Figure 4 – Frequency of Wave Encounter as a Function of Boat Speed in a State 4 Sea

Boat	Speed, knots	Heading	Sea Condition	Peak Acceleration g	Slams/Min
PCF	15.4	--	State 3	1.5	0.8
	22.5	--	State 4	5.5	10--30
PTF	40.0	Head	State 4	2.25	27
	27	Head	State 4	3.0	18
	31	Head	State 4	3.75	20
	40	Bow	State 4	3.5	18

A literature search has indicated that little past research is directly relevant to the topic of human reaction to repetitive impacts. One study[23] investigated repetitive shock-pulse effects on standing and supine volunteers caused by floor vibrations near drop forges or similar equipment. The results (Figure 5) indicated extremely small tolerable accelerations (10^{-3} g and less) which later investigators[24] consider to be "conservative."

TEST PROGRAM

NSRDC negotiated a firm fixed-price contract with the Washington office of the American Institutes for Research (AIR) for a detailed research plan designed to yield an assessment of the effects of repeated impacts on human performance. The contract included: (1) selection of an adequate performance test, (2) construction of an experimental design, (3) the development of data collection procedures, (4) description of statistical techniques, and (5) interpretation of results.

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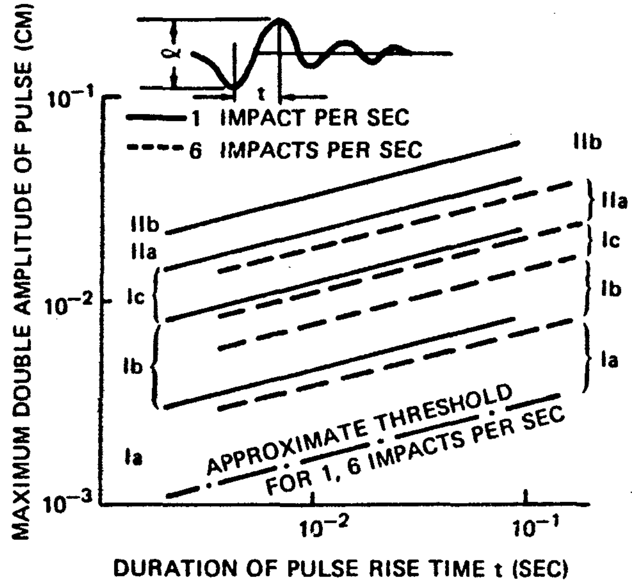
[23] Reiher, H. and F.J. Neister, "Die Emfindlichkeith des Menschen gegen Strosse," Forsch Geb. Ingenieurwessens, 3: 177 (1932).

[24] "Compendium of Human Responses to the Aerospace Environment," Vol. II, NASA CR-1205 (II) (Nov 1968).



THESE ARE REPRESENTATIVE OF IMPACTS FROM PILE DRIVERS, HEAVY TOOLS, HEAVY TRAFFIC, ETC. SUBJECTIVE REACTION IS PLOTTED AS A FUNCTION OF THE MAXIMUM DISPLACEMENT OF THE INITIAL PULSE AND ITS RISE TIME. THE NUMBERS INDICATE THE FOLLOWING REACTIONS: Ia, THRESHOLD OF PERCEPTION; Ib, EASY PERCEPTION; Ic, STRONG PERCEPTION, ANNOYING; IIa, VERY UNPLEASANT, POTENTIAL DANGER FOR LONG EXPOSURES; IIb, EXTREMELY UNPLEASANT, DEFINITELY DANGEROUS. THE DECAY PROCESS OF THE IMPACT IMPULSES WAS FOUND TO BE OF LITTLE PRACTICAL SIGNIFICANCE.

Figure 5 – Repetitive Shock–Pulse Effects on Standing and Supine Subjects in the Vicinity of Heavy Machinery

NSRDC followed the following AIR recommendations.[25] A compensatory tracking task was used as the performance criterion. Tracking error was scored continuously as the major dependent measurement. The factors that constitute the impact situation (impact level, frequency, and duration of the impact) were recorded and repeated.

In the tracking task layout chosen, a seated subject faces a cathode ray tube (CRT) mounted at eye level with the display surface of the CRT approximately 3.5 ft from the back of his chair. A center-mounted joy stick is provided to compensate for any motion of the "light" spot on the CRT. The display and joy stick controls are both mounted on the slam simulator along with the subject. Special attention was given to the shock and vibration mounting for the equipment. Figure 6 shows the test setup.

During the slam tests the subject attempted to track on the CRT a "light" spot that was driven in both the vertical and horizontal axes by a prerecorded random signal. The subject's tracking error as viewed on the CRT was measured and scored over time in terms of the algebraic sum of the error magnitude and was used in determining the degradation of his performance. Records were also made of slam frequency, amplitude, and pulse duration.

TEST APPARATUS

The basic equipment included the slam simulator and a performance measuring system (PMS) that consisted of a CRT, a tape recorder, a joy stick, and an absolute error integrator. Each component was assembled and coordinated with the other systems in order to obtain meaningful results. A short description of each system is given below.

Slam Simulator

The slam simulator is a pivoted platform that is raised on a spiral cam and then dropped onto either an adjustable shock absorber or a shock-absorbing foam. The slam simulator was developed at NSRDC and has undergone many modifications. The original shock absorber (4-in. stroke and 1-in.-diameter bore) was incapable of cushioning impacts low enough to be within ranges consistent with the proposed experiment. It has now been replaced by a shock absorber with an 8-in. stroke and a 2-in.-diameter bore (this can be completely replaced with shock-absorbing foam). Four additional improvements have also been made:

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[25] Farina, A.J., "An Experimental Plan for Assessing Human Performance in an Impact Environment," American Institutes for Research Report AIR-8-51-7/69-RP (Jul 1969).

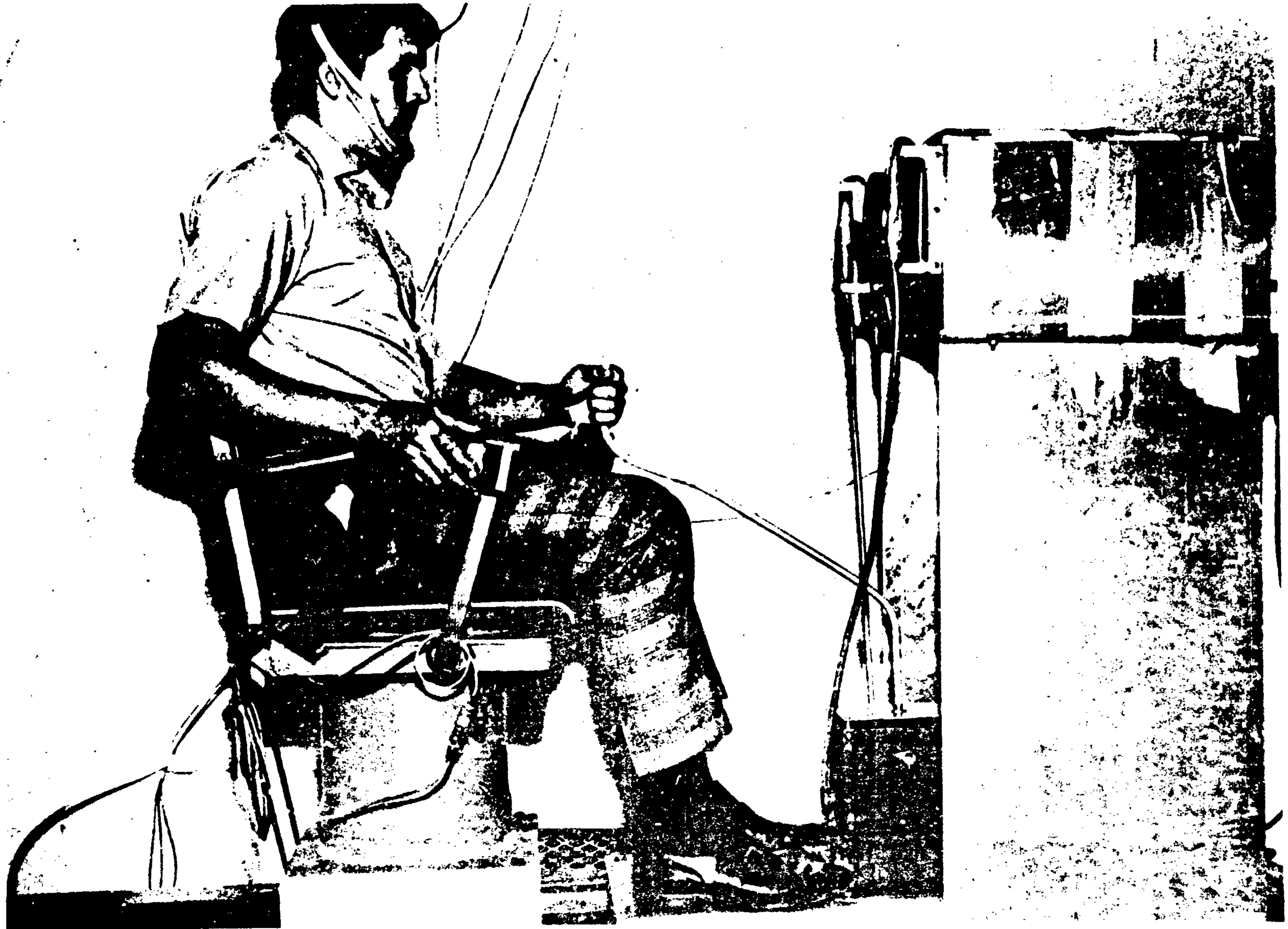

Figure 6 – The NSRDC Slam Simulator

1. The new shock absorber has been mounted at a 5-deg angle with the vertical to optimize the angle of impact and the subsequent travel.

2. The oil reservoir system has been refitted with larger diameter piping to avoid any line pressure buildup which would stiffen the shock absorber.

3. The steel cam follower has been replaced by a synthetic material, DELRIN, which cushions the upward impact of the cam against the cam follower.

4. A racing harness has been installed in the test chair to reduce forward body rotation of the seated subject.

PERFORMANCE MEASUREMENT SYSTEM (PMS)

The PMS, an electronic assembly that quantitatively measures subject performance, consists primarily of four components: a CRT, an FM tape recorder, a joy stick, and an absolute error integrator. The tape recorder provides a random signal (an illuminated point) along the screen of the CRT. The volunteer attempts to control the motion of the illuminated point by moving the joy stick up or down and left or right (a close analogy is the joy stick of an airplane). The absolute error integrator measures a subject's numerical performance in keeping the light spot in the center of the CRT.

The CRT is the familiar cathode-ray deflection plate tube similar to television picture tubes. The light trace it displays is driven by two independent sources, the tape recorder and the joy stick. The scope on the CRT system is analogous to coordinate paper and has an x, y origin at the center of the screen. Ideally, this coordinate system displays a linear relation between the instantaneous error reading and the displacement of the dot from the origin. In other words, the greater the distance from the crosshair, the greater the error.

The tape recorder uses nine 5-min random error (pretaped) programs to drive the CRT signal. (See Appendix B for the technique used to generate the random error program (tracking task forcing functions)). The nine programs all have different motion patterns, set individually each presents an almost identical degree of difficulty in tracking (1.5 percent maximum standard deviation for the uncontrolled error). The order of presentation of the nine programs is randomized so that a subject tracks a different program for each of the nine slamming runs; this arrangement prevents him from learning any one motion pattern too well.

The joy stick is mounted in a gear box which is attached to a universal shaft that allows two degrees of freedom of motion (within the geometric limits of the box). Movement of the universal shaft turns a vertical gear and a horizontal gear. The two gears, in turn, activate

two potentiometers whose turning is translated as horizontal and vertical deflections on the screen; they constitute the corrections made by the volunteer to the wandering signal.

The principle of the absolute error integrator is relatively simple. As the dot drifts away from the horizontal crosshair, it triggers progressively increasing positive voltages above the crosshair and increasing negative voltages below it. These voltages are stored in separate capacitors and added algebraically at the end of each run to obtain absolute error digital readouts. Vertical error readouts are resolved in an identical manner. Thus the horizontal and vertical performances are scored separately and simultaneously and can be analyzed independently. A timer with a maximum setting of 5 min activates the integrator and sets it off automatically. The error integrator, however, is meant only for rough approximation (±5 percent) of the numerical performance. It serves as a monitor during all testing. Precise readouts can be recorded simultaneously on a tape recorder and subsequently digitized and related to the physical input parameters.

The physical slam parameters are measured by a single accelerometer, velocity meter, and a time code generator. The frequency of impact is preselected by adjusting the speed of the motor that drives the cam. The accelerometer is mounted on the underside of the slam chair and measures the input impact levels. Unfortunately this accelerometer (like most accelerometers) is very sensitive to ringing and must be interpreted to get reliable input impact levels. Measurement of the input impact levels is accomplished by calculating the area under the acceleration time curve. The result of this integration (calculation) is the change in velocity (ΔV) which the subject experiences. With the velocity meter in place, a direct measurement of the impact level can be made. Figure 7 shows the present impact test range compared to data collected during the PTF-25 trials.[22]

SUBJECTS

Prospective volunteers were supplied by Contract Engineering Services, Inc., under a fixed price contract (N00 167-72-M-0449). The volunteers were young, healthy men in their early twenties, and some of them had previous experience with NSRDC single impact studies. All underwent intensive preliminary physical evaluations by two independent sources:

1. The Oscar B. Hunter Laboratories of Sibley Memorial Hospital performed a series of tests that included chest X-ray and radiologist report, electrocardiograph, and complete hematology laboratory.

2. An orthopedic surgeon (Dr. Kenneth Cho) issued a diagnostic impression on the basis of the past health history of a volunteer and a physical examination (thoracic, vertebral, and

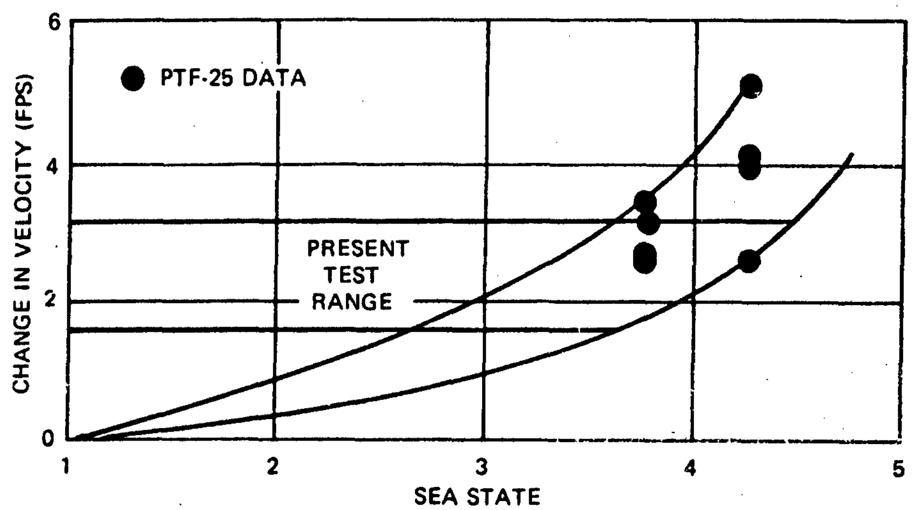

Figure 7 – Present Impact Test Ranges for the Slam Simulator

lumbosscral X-rays) (1) to ensure that no preexisting anomaly or musculoskeletal pathology was present and (2) to evaluate possible complications resulting from slam testing.

Permission for a volunteer to engage in slam testing was either granted or denied by the project medical officer on the basis of these two medical accounts. Each individual was also examined prior to every testing period. Thus, long-term effects (days, weeks) of previous testing could be assessed, and the individual could be temporarily excluded because of any minor complaint (cold, fatigue, etc.) unrelated to the study.

During the test, the medical officer was present to serve as a monitor. In addition, the subject was free to abort the test if he felt he could no longer tolerate the slamming motion.

EXPERIMENTAL DESIGN

Subjects were tested at various slam amplitudes, frequencies, pulse durations, and exposure times to determine tolerance limits and performance degradation levels. The initial testing involved short time exposures (5 min).

The subjective reactions of the volunteers were evaluated as a function of input parameters and performance degradation. The correlation between tolerance levels and performance degradation levels will be carried out later.

As already indicated, the three most significant parameters are the level of impact, the frequency, and the pulse duration. However, the small number of subjects did not permit a parametric analysis to be made by using the total range of each of these variables. Even if each factor is limited to three levels or values, which is the smallest number needed to establish a function, this would still yield a 3 x 3 x 3 design with 27 treatments or conditions. Assuming five test sessions per week, this would have run to 6 weeks of continuous testing for each subject. Even had they been available for that period and the project schedule permitted it, the risk of losing subjects increases when the number of sessions gets high. It was important, therefore, to reduce the number of testing sessions to a reasonable level.

One way to do this is to make an arbitrary judgment as to which one of the three factors is least likely to affect performance, or which is least likely to vary in the real situation. Whatever criterion is used, the net effect is that the number of treatments a subject undergoes is reduced from 27 to 9 by repeating measures only on the remaining two factors. It was decided to vary the frequency of impacts and impact levels and to hold the pulse duration constant. This led to a series of nine combinations for each pulse duration. Table 2 shows schematically how these parameters were varied.

PRELIMINARY SLAM TESTS

Tests on the NSRDC slam simulator were conducted in January of 1972 and again in February–March of 1973. The first series (Series I) consisted of two volunteers undergoing a selected sequence of impact levels and frequencies. This series was terminated due to the resignation of the medical officer and a lack of volunteers. In order to reduce the number of test sessions required of each volunteer, a second series (Series II) of tests began in February 1973. The intent of this series was to determine the reproducibility of each test session (thereby reducing the number of volunteers required and shortening the time required). These two tests series are now discussed in detail. A combination of the results of the two series is impossible due to extensive modification of the PMS between the two test series.

PERFORMANCE SCORES (SERIES I)

The first series was conducted on 4–6 January 1972 at the NSRDC Slam Facility. Appendix C gives the detailed procedure each subject underwent prior to testing. The project medical officer, Dr. P. Corrao, was in attendance at all times to ensure availability of proper medical assistance if needed and to collect pertinent medical data. Two volunteers began the testing program of nine 5-min runs on the slam simulator. The impact level (ΔV) was varied from 3.8 to 8.6 ft/sec and the frequencies were varied from 0.5 to 0.83 Hz (see Table 2). One volunteer completed the entire nine runs and the second only five.*

The test results can be seen in Table 3 which breaks down the performance scores for each run into horizontal, vertical, and total errors. Also listed are performance scores achieved by the volunteers while tracking on the PMS without undergoing slamming. (These scores are termed "dry run" scores and are explained further in Appendix C.)

Results of the Series I test are not altogether clear. Figures 8 and 9 show how the total performance scores changed in relation to the severity of the impact and the number of impacts per minute. It appears that the performance scores for Volunteer A in both the horizontal and vertical direction gave similar trends as did his total performance score (see Table 3). During these preliminary tests, there was a marked improvement in his performance scores for impact levels of 8.6 and 3.8 ΔV at 15 and 5 rpm, respectively. The implication is that a crew member could perform well in slamming environments approaching these

*This volunteer did not complete the entire nine runs because of the resignation of Dr. Corrao from his position at NSRDC and not because of physical reasons.

TABLE 2 – PARAMETER SCHEDULE

Pulse Time Duration (msec)	Change in Velocity ΔV (ft/sec)								
	3.8			6.8			8.6		
	Frequency (Hz)								
	0.5	0.25	0.083	0.5	0.25	0.083	0.5	0.25	0.083
15–40									
T_2									
T_3									

TABLE 3 – VOLUNTEER DATA SHEET, SERIES I

Run No.	Program	Horizontal Score	Vertical Score	Total Score	Impact Level (ΔV FPS)	Impacts per Minute rpm	Volunteer	Test Date	Dry Run Score Total
1	3	197	105	302	6.8	5	A	4 Jan 1972	392,243,229
2	3	189	120	309	6.8	15		4 Jan 1972	--
3	3	212	178	390	3.6	30		4 Jan 1972	--
4	4	145	113	258	3.6	5		5 Jan 1972	160,163,161
5	4	141	121	262	8.6	15		5 Jan 1972	--
6	4	186	218	404	6.8	30		5 Jan 1972	--
7	5	214	177	391	8.6	5		6 Jan 1972	369,349,328
8	5	232	271	503	8.6	30		6 Jan 1972	--
9	5	207	193	400	3.6	15	A	6 Jan 1972	335
1	5	157	154	311	6.8	15	C	6 Jan 1972	175,180
2	5	224	263	487	6.8	30			--
3	5	209	182	391	8.6	5			--
4	6	208	206	414	3.6	15			340,325,341
5	6	241	262	503	8.6	30	C	6 Jan 1972	--

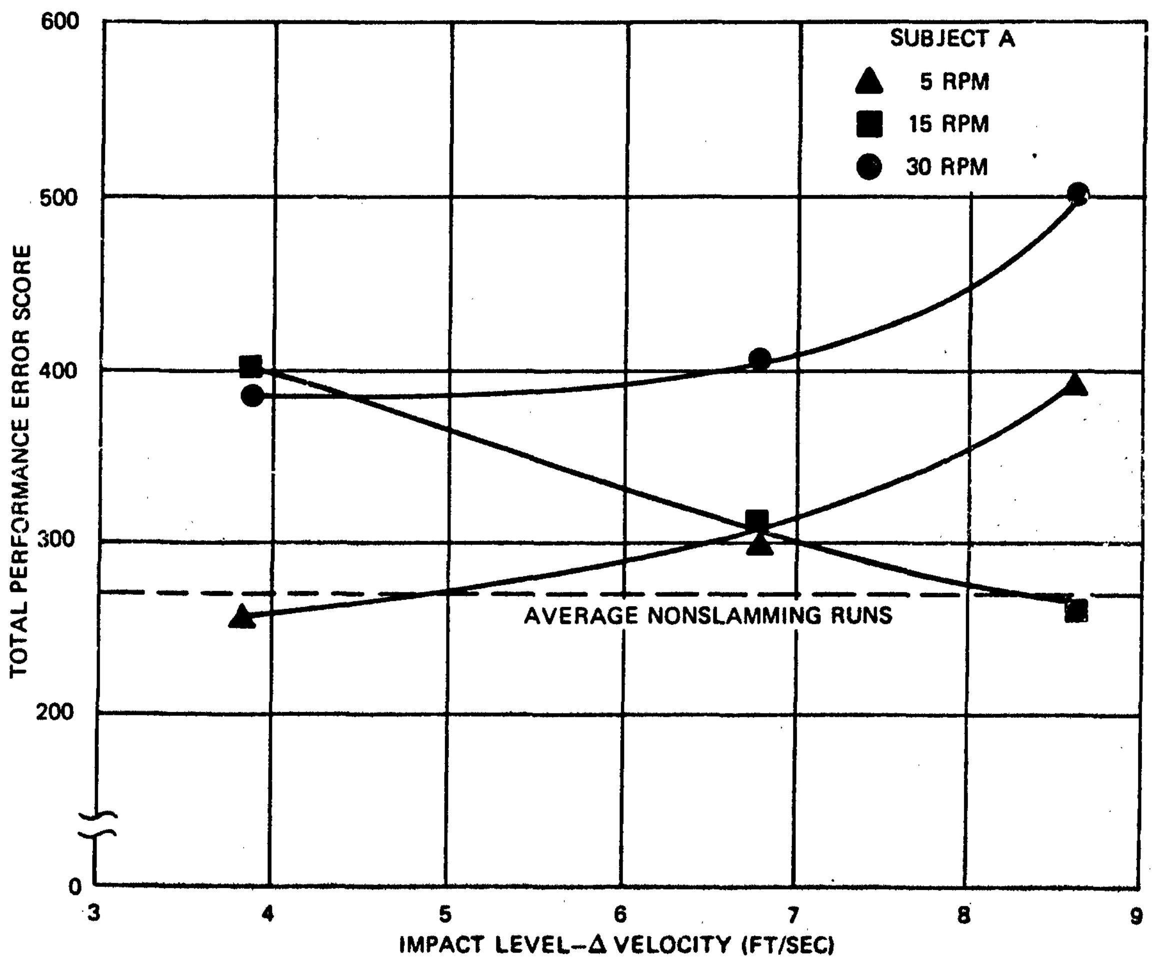

Figure 8 – Performance Scores of Volunteer A, Series I

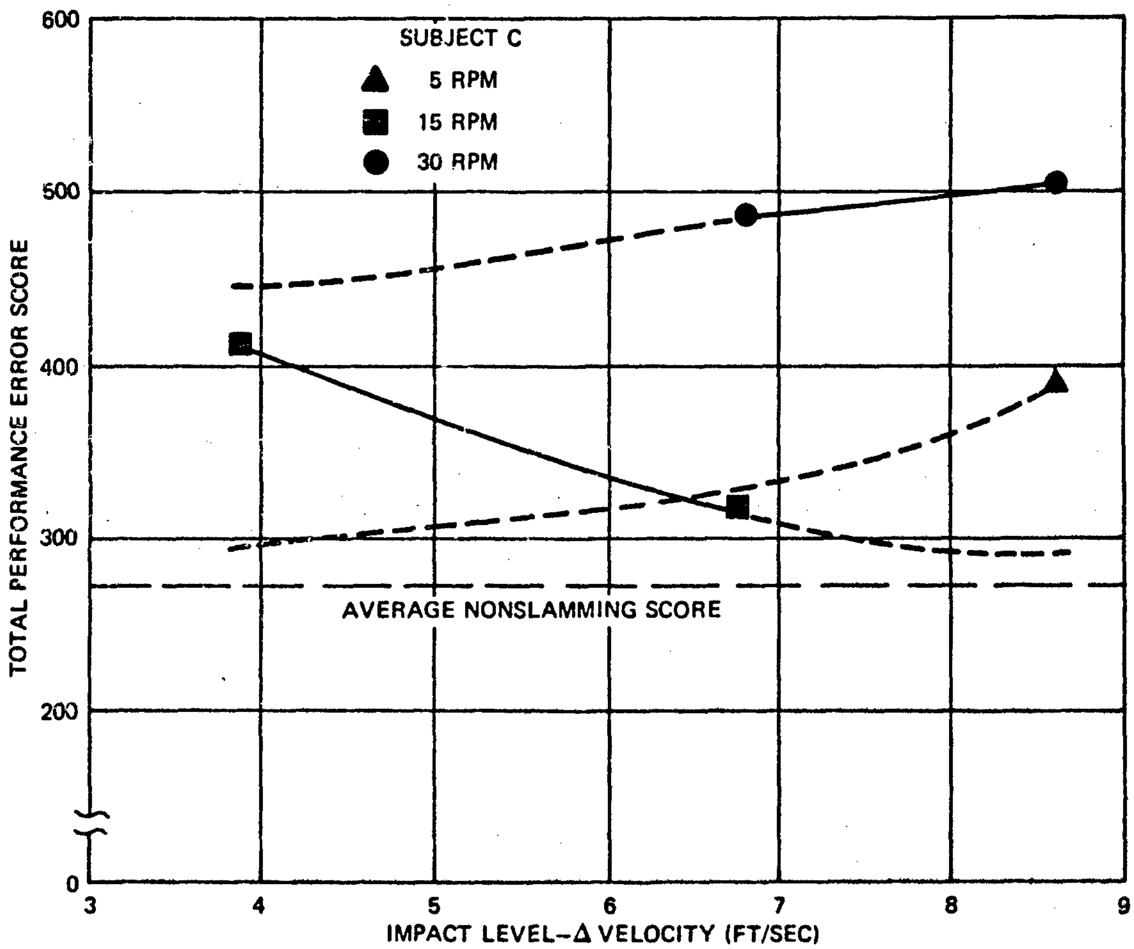

Figure 9 – Performance Scores of Volunteer C, Series I

magnitudes. Although Volunteer C did not complete the nine 5-min runs, his performance scores indicated similar trends for 3.8 ΔV at 5 rpm and 8.6 ΔV at 15 rpm. This can be seen in Figure 9 where the dashed lines indicated expected trends.

Subjective Reactions

After each run, the volunteer rated the session subjectively from extremely enjoyable to extremely unpleasant. Table 4 lists these subjective reactions for each trial run. Volunteer A felt Sessions 5 and 7 were the most uncomfortable and rated them mildly unpleasant. These sessions respectively correspond to 8.6 ΔV at 15 rpm and 8.6 ΔV at 5 rpm. Although Volunteer A rated these sessions as the most unpleasant, his performance scores at these impact levels were not poor (see Figure 8). In fact, he achieved his second best score during Session 5.

Similarly, Volunteer C rated Session 3 (8.6 ΔV at 5 rpm) as the most uncomfortable of his five runs (see Table 3), yet on this session his score was midway between his best and worst scores. However, this combination of 8.6 ΔV and 5 rpm is one of the same combinations that Volunteer A termed the worst. It thus appears that this particular combination is one of the least enjoyable. Nevertheless, the volunteers were able to score relatively well at this combination. It can be concluded from this preliminary data that the subjective reactions of the volunteers did not appear to relate to their performance.

Medical Findings

The medical officer was present during all phases of testing. His evaluation immediately after the experiment consisted of specifically directed questioning, a rapid physical examination with special reference to the musculoskeletal system, determination of visual acuity and a rapid urinalysis to ascertain the presence of hematuria or proteinuria.

The specific test period was terminated either by the experimental design or at the expressed request of the volunteers for whatever reason. The latter occurred very infrequently, never for musculoskeletal complaints, and always for minor reasons such as fatigue, vague general discomfort, headache, etc. These symptoms tended to be of a random, unpredictable nature; they were unrelated to specific test duration, frequency, or intensity, and they rapidly reversed following cessation of the test.

It was concluded that from a medical point of view, these tests were extremely well tolerated. No instance of soft or bony tissue injury occurred nor was hematuria or proteinuria

TABLE 4 – SUBJECTIVE REACTION OF VOLUNTEERS, SERIES I

Rating	Volunteer A Runs									Volunteer C Runs				
	1	2	3	4	5	6	7	8	9	1	2	3	4	5
☐ +4 Extremely enjoyable. I was disappointed that the machine stopped so soon.											X			X
☐ +3 Very enjoyable.										X			X	
☐ +2 Enjoyable. I'm looking forward to riding the machine again.												X		
☐ +1 Mildly enjoyable.		X	X	X				X	X					
☐ 0 Neutral reaction. Pleasant at times—unpleasant at others.	X					X								
☐ −1 Mildly unpleasant.					X		X							
☐ −2 Unpleasant. I was fairly glad the ride was over.														
☐ −3 Very unpleasant.														
☐ −4 Extremely unpleasant. The ride was so alarming that I could barely stand it.														

ever recorded. Indeed, neither volunteer had to be eliminated from testing either at his own request or for any medical reason, and practically all the tests were concluded without interruption by the medical officer or the involved individual.

REPRODUCIBILITY OF PERFORMANCE SCORES (SERIES II)

The second series was conducted between 12 February and 13 March 1973 at the NSRDC Slam Facility in order to determine the reproducibility of each test session data. Three impact levels (2.1, 2.7, and 3 fps) and three frequencies (30, 15, 5 rpm) were used (the pulse duration was kept constant at 40–50 msec), leading to a nine-session test series. Each 5-min session was to be repeated three times (total number of sessions = 27) in a random manner using a single volunteer. (This volunteer was Volunteer C of the first test series.) Only 21 of the 27 test sessions were actually completed. Testing was terminated when the volunteer incurred a back discomfort which caused the attending medical officer to cancel further tests. Details of this incident are discussed later. A minimum of 30 min between each test run was allowed to ensure that the volunteer was not fatigued or bored during the test runs.

Results for the 21 sessions that were completed are shown in Figure 10. Note that as either the impact level or the number of impacts per minute increased, the total error increased. One would expect this trend to result in a series of curves for different impact rates. A least squares analysis of the 21 data points provided the following equation:

$$\underline{ES = -11518 + 458\,(IPM) + 7241\,(IL)}$$

where ES is the error score,

IPM is the impacts per minute, and

IL is the impact level (change in velocity V) in feet per second.

The index of correlation is 0.95, meaning that the data were very reproducible. The clustered data points verify the reproducibility of the test sessions as seen in Figure 10. Also shown in the figure is the volunteer's basic ability to track (average nonslamming or dry run score). Table 5 lists the error scores, variables, and test conditions used in this second test series, including the dry run scores.

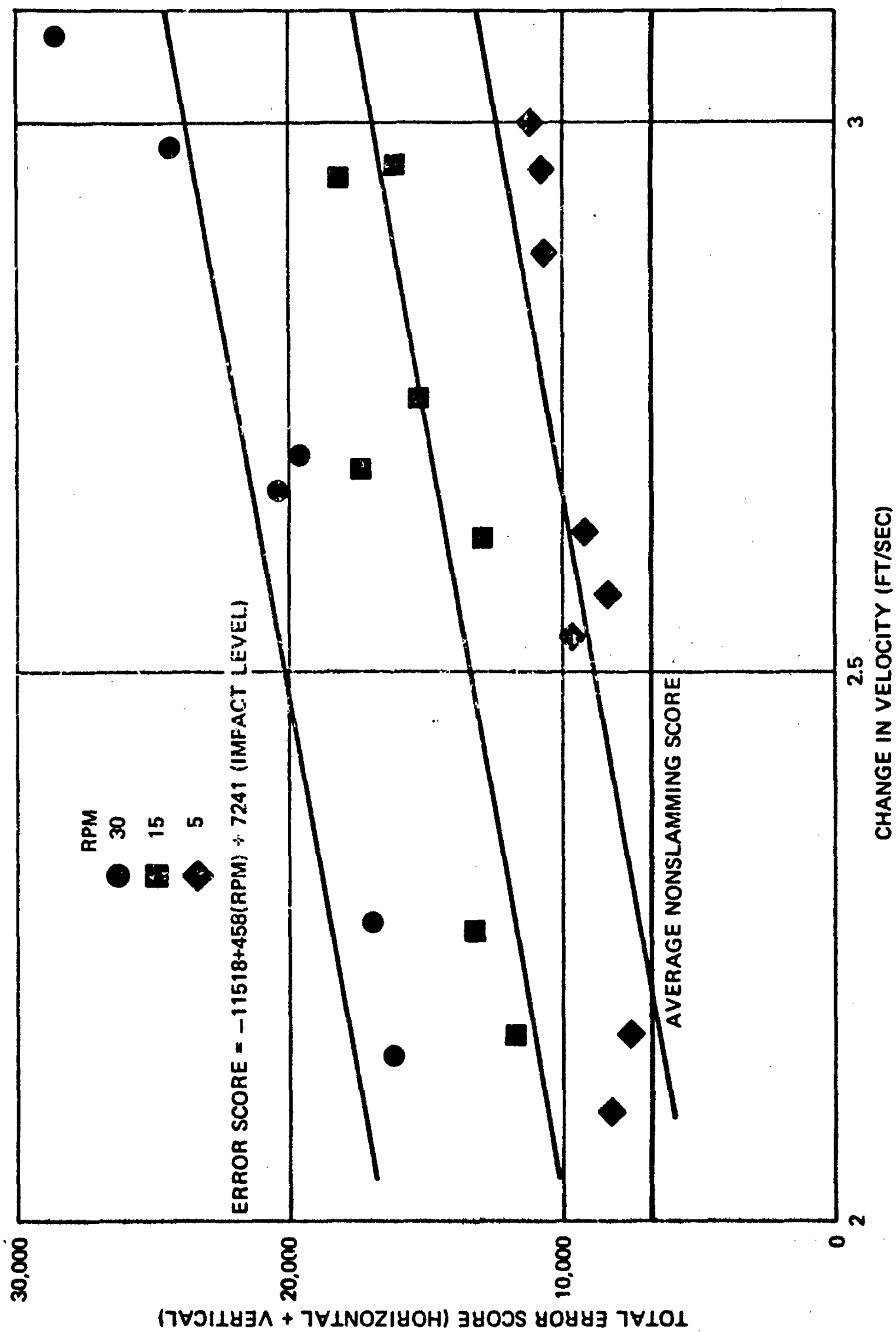

Figure 10 — Performance Degradation of Volunteer A, Series II

TABLE 5 -- VOLUNTEER DATA SHEET, SERIES II

Run No.	Program	Horizontal Score*	Vertical Score*	Total Score*	Impact Level ΔV ft/sec	Impacts per Min rpm	Dry Run Score Total	Test Date & Time
1	2	7,472	8,734	16,206	2.15	30	5,690 8,860	2/12/73 1:00
2	9	10,219	8,076	18,295	2.94	15	9,676	2/12/73 1:45
3	3	10,599	6,721	17,320	2.78	15	10,244	2/12/73 2:30
4	4	4,942	3,202	8,144	2.1	5	5,342 5,575	2/13/73 1:00
5	5	6,378	4,284	10,662	2.87	5	5,224	2/13/73 1:30
6	7	6,078	5,780	11,858	2.17	15	7,718	2/13/73 2:00
7	1	4,842	4,805	9,647	2.53	5	4,371 5,587	2/14/73 1:00
8	8	11,428	12,978	24,406	2.97	30	5,295	2/14/73 1:45
9	6	9,117	11,093	20,210	2.67	30	5,042 5,802	2/15/73 1:45
10	9	4,602	3,606	8,208	2.57	5	5,222	2/15/73 2:30
11	6	9,127	10,582	19,709	2.7	30	5,233 7,323	2/21/73 1:30
12	2	6,438	6,356	12,794	2.62	15	4,538 4,659	2/23/73 1:30
13	5	4,478	2,790	7,268	2.17	5	5,666	2/23/73 2:30
14	8	5,696	4,970	10,666	2.96	5	5,193 7,221	2/26/73 12:30
15	3	7,874	8,482	16,356	2.96	15	16,643	2/26/73 2:00
16	1	8,593	8,496	17,089	2.28	30	4,493 6,660	2/28/73 1:00
17	4	6,592	6,772	13,364	2.27	15	4,971	2/28/73 2:00
18	7	15,078	13,890	28,968	3.07	30	6,435 11,388	3/ 2/73 2:30
19	9	4,754	6,328	11,802	3.02	5	7,806 7,836	3/ 9/73 2:00
20	4	7,161	7,438	14,599	2.75	15	8,244	3/ 9/73 3:00
21	8	4,119	5,156	9,275	2.63	5	5,553 5,568	3/13/73 1:30

*A score of 120,000 is equivalent to an error of 1.97 in.

Subjective Reactions

Table 6 indicates the subjective reactions after each test session of Series II. Little or no correlation could be found between the test conditions, error scores, and the subjective reactions of the volunteer. Overall, the volunteer was able to perform as expected even when he felt the slamming conditions were unpleasant.

Medical Findings

During the Series II tests the subject's blood pressure, pulse, visual acuity, urinary function, and general physical condition were evaluated. No significant change was noted until the last test day when the session was terminated after the subject complained of back pain.

This complaint was evaluated by physical examination, X-rays of the spine, and urinalysis. A consultation was held with an orthopedic surgeon to determine the nature of the complaint and the possibility of structural damage to the subject's back. These initial evaluations suggested strain of the paravertebral muscles, and the subject was treated with muscle relaxants and analgesics. Subsequent continued observation suggest that the initial diagnosis was correct. A reevaluation by the orthopedic consultant showed no evidence of fracture or disc disease. The subject is presently on no medication, medical supervision or restrictions, and has no pain.

However, the orthopedic consultant advised that the present volunteer should not be used for further testing. Although the subject's complaint was considered to be of a minor nature, it is the opinion of the medical consultant that any volunteer who develops any evidence of injury secondary to the testing procedure should be eliminated from future testing.

CONCLUSIONS

Several significant conclusions can be drawn from the two series of simulated slamming tests. As expected, performance error (tracking task) increases with increased impact level and impact frequency. This degradation in performance increased continuously at 5 and 30 impacts/min but the rise in error was followed by a noticeable decrease at 15 impacts/min. Further tests would have to be considered in an attempt to explain the reversal in error score at this impact frequency. The data from Series II were found to be very reproducible, thus justifying single test sessions.

TABLE 6 – SUBJECTIVE REACTION OF VOLUNTEERS, SERIES II

Rating	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
☐ +4 Extremely enjoyable. I was disappointed that the machine stopped so soon.																					
☐ +3 Very enjoyable.								X							X						
☐ +2 Enjoyable. I'm looking forward to riding the machine again.		X					X														
☐ +1 Mildly enjoyable.				X					X	X						X	X		X	X	X
☐ 0 Neutral reaction. Pleasant at times–unpleasant at others.			X		X	X						X		X				X			
☐ –1 Mildly unpleasant.																					
☐ –2 Unpleasant. I was fairly glad the ride was over.	X										X		X								
☐ –3 Very unpleasant.																					
☐ –4 Extremely unpleasant. The ride was so alarming that I could barely stand it.																					

Subjective reactions were unrelated to either the error score or the input variables. What man considers to be uncomfortable does not distract from his ability to function, i.e., as the ride became more unpleasant (subjectively), the errors made in the tracking task did not increase. Increasing the duration of the test session until the volunteers request its termination would seem to be a reasonable next step in determining human tolerance levels and performance degradation due to small boat slamming.

No changes were noted in the volunteer's blood pressure, pulse, visual acuity, urinary function, or general physical condition. No serious muscular skeletal discomforts were noted and in general the volunteers tolerated the test quite well.

ACKNOWLEDGMENTS

The authors are grateful for the technical assistance of Mr. E.V. Pickford in operating the necessary electronic equipment and for his many helpful suggestions. Many thanks are owed to Mr. Paul Haldeman who redesigned the performance measurement system and rendered quick and reliable assistance whenever operational difficulties arose.

APPENDIX A
BIOMECHANICAL AND IMPACT STUDIES

Considerable information is available from studies of human response to vibration by researchers in the transportation, aviation, naval, and automotive fields.[9–19, 23–46] Similarly,

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[26]Grande, D.L., "Some Effects of Random Turbulence on Weapon System Performance," Aerospace Engineering (Oct 1962).

[27]Parks, D.L. and F.W. Snyder, "Human Reaction to Low Frequency Vibration," Boeing Document D3-3512-1 (Jul 1961).

[28]Hirsch, A.E., "Man's Response to Shock Motion," David Taylor Model Basin Report 1797 (Jan 1964).

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[30]Seireg, A. Kempe, "Behavior of *in Vivo* Bone under Cyclic Loading," ASME Report 69-BHF-8 (Jun 1969).

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[32]Goldman, D.E., "A Review of Subjective Responses to Vibratory Motions of the Human Body in the Frequency Range 1–70 CPS," Naval Medical Research Institute Report 1, NM 004-001 (1948); ASTIA ATI 47 359.

[33]Goldman, D.E., "Mechanical Vibration and Its Effects on Man," Naval Medical Research Institute Lecture and Review Series 52-1 (6 Feb 1952); ASTIA AD-6179.

[34]Goldman, D.E. and H.E. Von Gierke, "The Effects of Shock and Vibration on Man," National Medical Research Institute (8 Jan 1960); ASTIA AD-241,621.

[35]Evans, F.G. and H.R. Lissner, "Biomechanical Studies on the Lumbar Spine and Pelvis," Journal of Bone and Joint Surgery, 41A: pp. 278–290 (1959).

[36]Brown, T.R. et al., "Some Mechanical Tests on the L-S Spine with Partial Reference to the IV Discs," Journal of Bone and Joint Surgery, Vol. 39-A, No. 5, pp. 1135–1164 (1957).

[37]Hardy, W.G. et al., "Repeated Loading Tests on the Lumbar Spine," Surgical Forum, Vol. 9, pp. 690–695 (1959).

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[39]Garrick, J.G. et al., "Post Graduate Medicine," Vol. 43, pp. 117–121 (Feb 1968).

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[41]Pilguard, S., "Stress Fracture of the Os Calcis," Vol. 34, pp. 270–272, ACTA Orthopaedica Scandinavica (1968).

[42]Levy, P.M., "Ejection Seat Design and Vertebral Fractures," Aerospace Medicine, Vol. 35, No. 6, p. 545 (Jun 1964).

[43]Linder, G.S., "Mechanical Vibration Effects on Human Beings," Aerospace Medicine, Vol. 33, No. 8, p. 939 (Aug 1962).

[44]Hirsch, C. and A. Nachemson, "New Observations of the Mechanical Behavior of Lumbar Discs," ACTA Orthopaedica Scandinavica, Vol. 23, pp. 254–283 (1954).

[45]Roaf, Robert, "A Study of the Mechanics of Spinal Injuries," Journal of Bone and Joint Surgery, Vol. 42-B, pp. 810–823 (Nov 1960).

[46]Guignard, J.C., "Vibration," Textbook of Aviation Physiology, Pergamon Press, Glasgow, pp. 813–891 ( ).

extensive research has been done on human tolerance to impact, particularly in relation to modern aircraft ejection systems.[34, 47-54] The vibration studies have involved frequencies of 1 Hz and above and amplitudes of varying ranges. The amplitudes of permissible exposure have been determined experimentally and noted at each frequency, as perceptible, tolerable, and intolerable for various time periods.[29] Extensive psychophysiologic studies have been performed to evaluate human response to various levels of vibration.[29, 55-60]

A very thorough survey of studies on human response to vibration[7] states as follows: "We find that experimental data are largely in agreement with criteria recommended by the International Organization for Standardization and extend these criteria to higher frequencies ..... At low frequencies (0.05 - 2 Hz), however, the data are so disperse that we are unable to establish any meaningful criteria." This report recommended that the ISO criteria (which are shown in Figure A.1) be used when setting the maximum tolerable acceleration ("g levels") for frequencies from 2.0 to 1000 Hz for different duration times. The only notable exception found when actual data were checked against the ISO criteria is the low-frequency region from 0.7 to approximately 2 Hz; here the discomfort and tracking curves

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[47] Chubb, R.M. et al., "Compressive Fractures of the Spine during USAF Ejections," Aerospace Medicine (1965).

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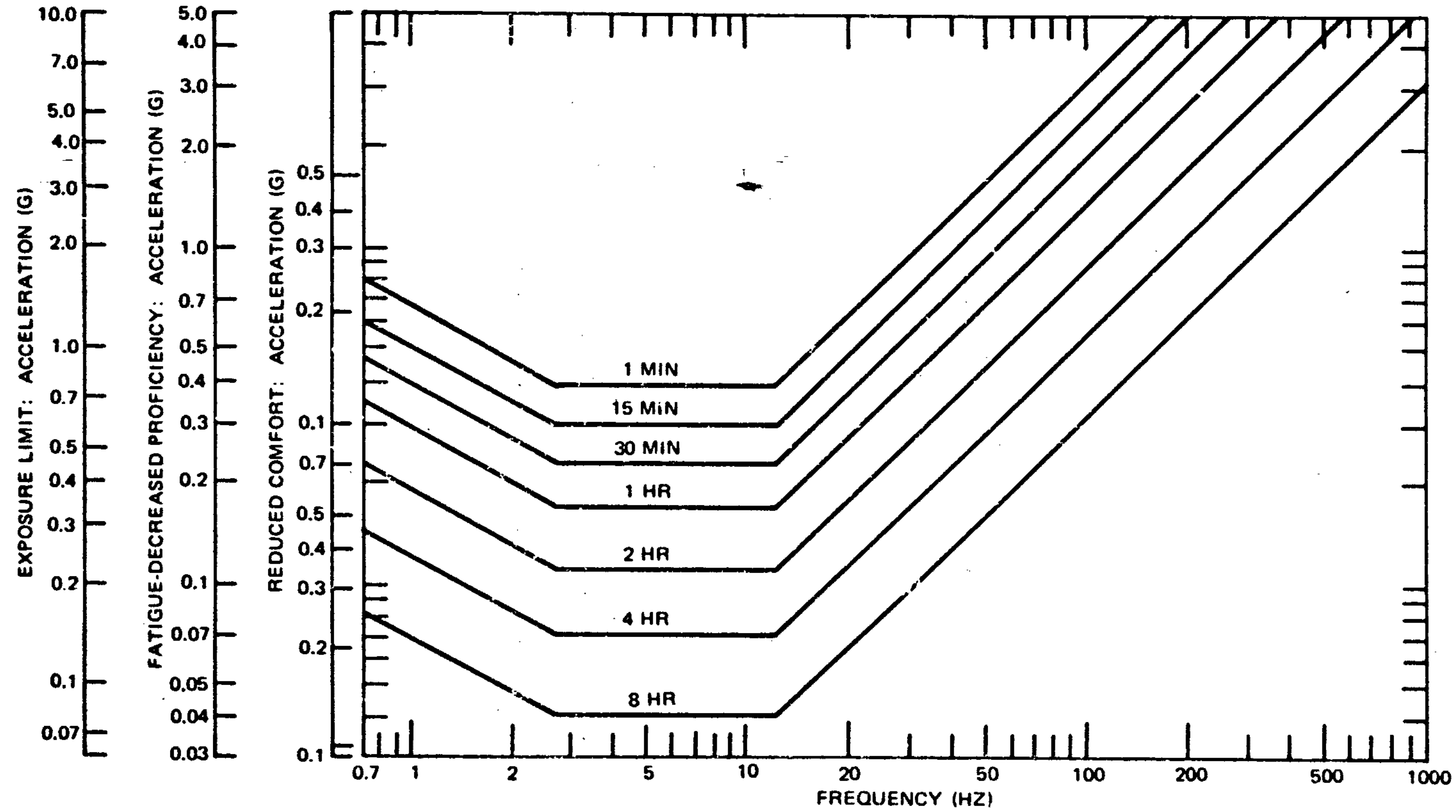

Figure A.1 – Vibration Criteria Established by International Organization for Standardization

(From Bender and Collins[7])

decrease substantially with decreasing frequency whereas the ISO curves increase.[7] This report points out very clearly that in the frequency range of interest (0.1 to 1.0 Hz), data are not available to establish criteria for man's performance and tolerance to repetitive slams.

The frequency range between 0.1 to 0.5 Hz is known to be significant in repetitive ship slamming. The range of g-forces of interest extends to 10 g. It should be noted that there is an inverse relationship between frequency and g-forces. This frequency range concerns an area of investigation where little or no data are available on human response. The only related information available in the frequency range 0 to 1 Hz is for motion sickness and subjective tolerance of drop-forge operations.[23, 24, 61], (refer to Figure 5).

Available data from aircraft ejection systems give an indication of seated man's tolerance to single impact. The long history of research in this field dates back to German studies in World War II.[51] This research proceeded from static loading on cadaver vertebrae to dynamic loading during ejections of live volunteers. It was found in the latter case that three out of four men suffered compression fractures from a peak acceleration of 26 g for 0.005 sec. Catapult forces were reduced so that peak acceleration did not exceed 20 g.

Although jolt or rate of rise of acceleration (da/dt) was recognized as important, it was not well understood. In the United States, for example, Watts performed 60 experiments on 26 seated volunteers during 1946. Acceleration ranged from 18 - 21 g at various rates of onset without the occurrence of significant vertebral injury.[56] Subsequent work not only documented the significance of the rate of rise of acceleration (da/dt) but also the importance of correct alignment of the vertebral column at the time of ejection.[47, 50, 52-53] Only a few years ago there was general agreement in the United States that on initial positive acceleration at a rate of onset of 250 to 300 g/sec, a peak of 20 to 21 g was acceptable for a duration of less than 0.1 sec, provided the spine was *properly positioned*.[42] Recent reports from Wright-Patterson Air Force Base now indicate that there is still a 5-percent risk of vertebral injury at 18 g. This information does indicate an approximate value of permissible g-forces for a single impact.[48]

The availability of sufficient data on the degradation of performance as a function of acceleration, frequency, and exposure time would enable estimates to be made of the effects of slamming accelerations on performance. Unfortunately, this information is not available. Numerous investigators have experimented with various aspects of the problem, but differences in techniques preclude combining the results.

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Vertebral fatigue fracture secondary to repetitive impact has not been described in medical literature. Fatigue fracture of bone has been described as occurring in the os calcis,[41] the metatarsals,[40] and in vertebral spines in relation to clay shoveling.[39] Quantitative studies, however, are not available.

In vitro studies of vertebrae and intervertebral disks indicate that 1100 lb will fracture the vertebral end plate.[62] Studies with cadavers show that a single impact force of 15 g will fracture the vertebral end plate.[63]

A rule of thumb used in metallurgy would suggest that the endurance load limit is about 50 percent of the static fracture load. This rule can be corroborated somewhat by an *in vivo* study of cyclic loading of a rat tibia; the endurance load limit was found to be 42 percent of the static fracture load.[30] The results suggest endurance load limits of 5 and 7 g based on the cadaver figures of Perey and Patrick, respectively.

In vivo fatigue testing of both fresh and embalmed human cadaver vertebrae was reported by Hardy, et al.[37] The fresh vertebrae, obtained from a 48-year old man, were tested cyclically at a peak load of 785 lb occurring 120 times/min. Fracture was observed after some 1,290,000 consecutive loading cycles. The 785-lb force applied to a spinal section would be equivalent to that obtained by applying an 8-g load to a 200-lb man in a sitting position 120 times/min for approximately 8 days. Other data using embalmed vertebrae from individuals in the fifth and sixth age decades are shown below:

Load (lb)	Cycles to Fracture
500	539,000
750	401,206
900	182,300

Note also that hundreds of thousands of *consecutive cycles* are needed to cause fracture. If living humans were tested at similar loadings but at only 50 to 600 consecutive cycles per day, as expected in the planned tests, fracture possibilities would seem remote considering that the participation of any one individual would hardly exceed a total of 2000 intermittent cycles spread over a period of weeks. On the basis of the Hardy data alone, the planned test procedure would seem to be within bounds that are as conservative as possible yet still permit useful information to be obtained while reducing injury possibilities to the vanishing point.

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APPENDIX B
TRACKING TASK FORCING FUNCTIONS

Separate forcing functions were generated for each axis of the two-dimensional tracking task. Each forcing function was composed of the sum of four randomly selected sine waves from a list of 10 sine waves of equal amplitude. The frequencies of the component sine waves (given below) were spaced in fairly even steps between 0.075 and 0.509 rad/sec, but harmonic relationships were avoided.

Sine Wave	Frequency (rad/sec)
1	0.075
2	0.124
3	0.172
4	0.220
5	0.268
6	0.316
7	0.365
8	0.413
9	0.416
10	0.509

Each selected frequency was set on a separate wavetek generator. A digital counter was used to ensure that the signal frequency was ±10 percent of the intended frequency. Direct counting was not possible at the low frequencies, but it was possible to measure the period of the signal. Simultaneously an oscilliscope set at 2 v peak to peak was used to check the amplitude of the signal. With the four frequencies set on the waveteks, a four-channel adder was used to add the signals. The final signal was then recorded on an FM tape for 5 min.

Error controls on the tracking task forcing functions were set at all times to provide an average absolute horizontal deflection of 0.4 in. and an average absolute vertical deflection of 0.56 in. on the CRT. In other words, with the joy stick lock in the zero position the forcing function drove the light spot on the CRT in such a manner that the average absolute deviation from the center of the CRT was 0.4 in. on the horizontal axis and 0.56 in. on the vertical axis.

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APPENDIX C
HANDLING OF VOLUNTEERS

Once the volunteer reports to Code 1747, he is taken to the Slam Testing Facility. He then experiences the following sequence of events (see Table C.1):

1. He listens to a short prepared talk that describes the slam experiment.

2. Knowing the nature of the project more fully, he can now decide whether to sign a voluntary consent statement (Consent to Participate Voluntarily in a Research, Development, Test, or Evaluation (RDT&E) Procedure). If so, he continues with the sequence.

3. The volunteer fills out a two-part questionnaire. Part One is intended to uncover personal factors that might relate to the outcome of the testing, such as amount of sleep and interest in the project. Part Two identifies previous experiences analogous to a ship slam environment.

4. The volunteer begins the baseline physical examination by identifying trouble areas in his medical history. This questionnaire serves primarily as a cross-check since extensive physical examinations have already been performed by a medical laboratory and by an orthopedic surgeon.

5. The Code 1747 medical consultant administers baseline physical examinations to the volunteer: respiration, pulse, blood pressure, visual acuity, and urinalysis.

6. Anthropometic measurements are now taken by photographing the volunteer in a series of postures against a linear grid system (seated body dimensions, breadth and depth dimensions). Since the four postures depicted on the data sheets can be recorded permanently on film, any other body dimensions deemed relevant after the testing can be accurately picked off the photographs. To aid in the accurate reading of body dimensions, parallax corrections have been calculated for all the four postures.

7. The volunteer is exposed to a sequence of impacts aboard the simulator but without performing the tracking task. The sequence will proceed from 2.0 to 8.6 ΔV ft/sec. At each impact level, there will be five slams at 0.25 Hz. Although this slam sequence is intended to reduce any anxiety concerning the severity of the test, the subject is free to cancel his participation in the experiment at any time.

8. The volunteer acquaints himself with the CRT and joy stick. The light trace is on the CRT without a random program.

9. At this time a sequence of nonslamming runs begins and is repeated for each volunteer. Without any motion of the slam simulator, random signal runs of 5-min duration are tracked until consistent scores are recorded. (Since the integrator is only 5 percent accurate, two consecutive scores within 5 percent of each other will be interpreted as consistent scores.) To circumvent the effects of anxiety and warmup, only the last 4 min of 5-min runs are actually scored.

10. The volunteer tracks a random signal for 5-min with the simulator in motion at a preselected g-load and frequency. The scores are recorded.

11. The subject characterizes the severity or discomfort of the last ride by choosing the appropriate description on the Subjective Reaction Form. A scale of +4 to --4 was chosen to include the possibility that the volunteer found the ride either enjoyable (positive values) or alarming (negative values). This nine-point scale, together with the nine different test conditions, enables a 9 x 9 matrix which lends itself to a Latin Square statistical analysis.

12. The volunteer repeats a nonslamming run (dry run) with the same random signal program. This score is compared with the first nonslamming (dry run) run to determine the effect of slamming experience on the volunteer's steady-state ability to track.

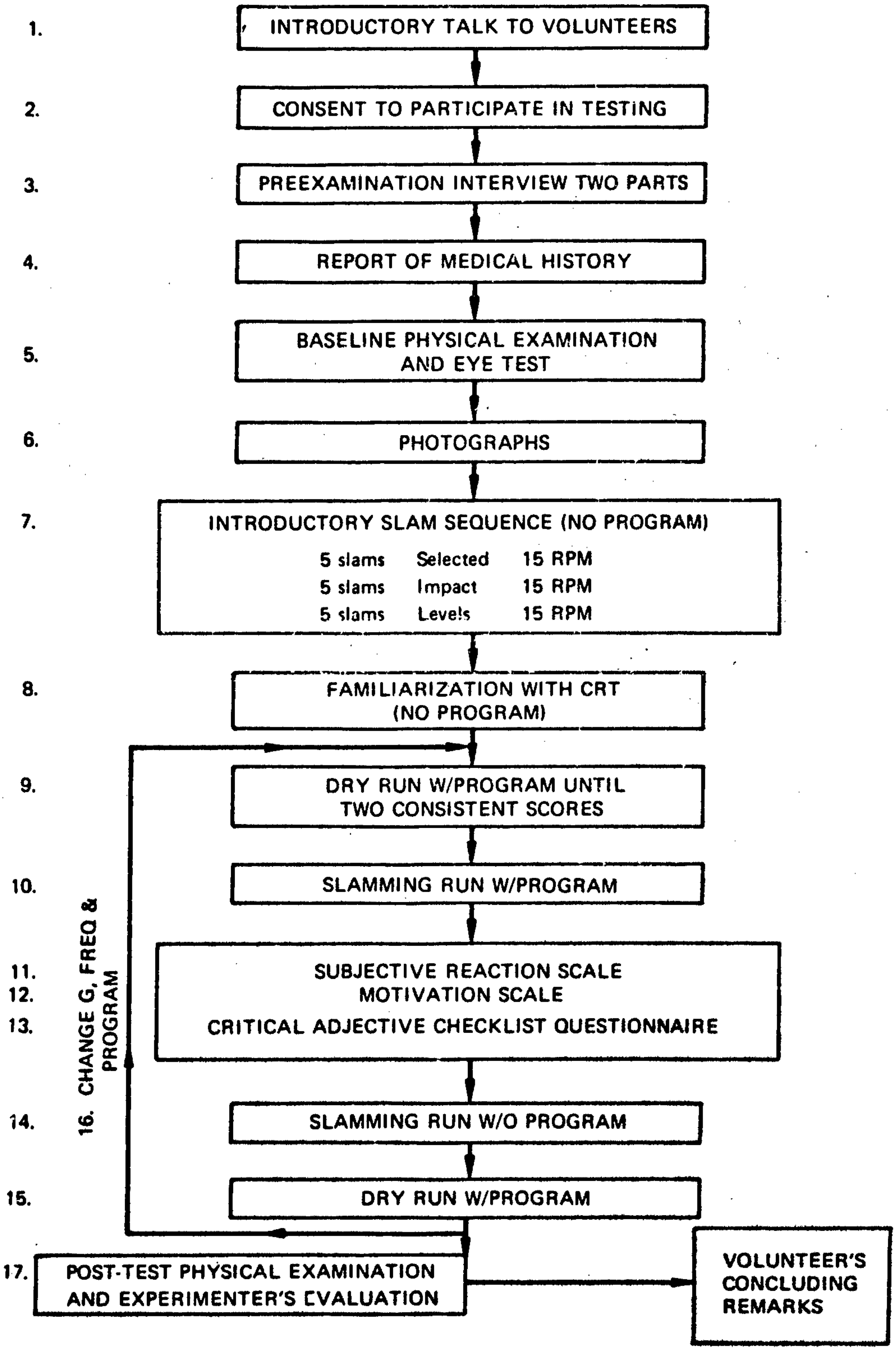
13. The sequence begins again at Item 9 with a new g-loading, frequency, and random error program until all nine input conditions have been completed.

14. The medical consultant administers the post-test physical examination and determines any physiological differences between the pre- and the post-test physicals.

15. The volunteer records his impressions of the test procedure and evaluates the hardware and subjective tests.

(A flow chart of this procedure is presented as Table C.1.)

TABLE C.1 — SEQUENCE IN HANDLING VOLUNTEERS



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